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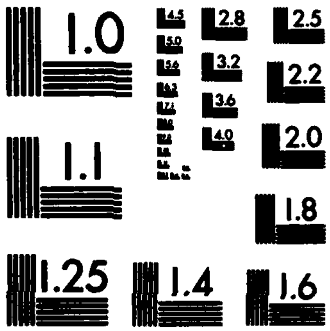
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FOREIGN TECHNOLOGY DIVISION

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by

L. Antal and J. Uczkiewicz

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OUTLINE OF METHODS FOR DESIGN OF SUPERCONDUCTING TURBOGENERATORS

Ludwik Antal and Jacek Uczkiewicz

Most Important Notation

A_s = specific electric loading of stator
B = magnetic induction
c, d, x, y
z, v, u, L = dimensional coefficients
D = diameter
i, I = current
j = current density
k_w = filling factor
l = length
l_{0a} = calculated length of armature winding
n = rotational velocity
r, R = radius
S = apparent power
T = time constant
γ = electric conductivity
Δ = shield thickness
λ = relative permeance
μ_g, μ^* = magnetic permeability
ϕ = phase shift angle
ω = angular frequency

Introduction

Work on synchronous generators with a superconducting excitation winding is going on in the most important scientific-research centers in many countries. The programs of activities undertaken in this field are being realized very persistently, and everything indicates that superconducting turbogenerators already occupy a permanent place among electric machines. The efforts of scientific teams are currently being concentrated on several very difficult problems. The latter include heat calculations of a rotor comprising a superconducting winding cooled by liquid helium, electromagnetic calculations of the excitation winding shielding system, dynamic stability studies, strength calculations of the supporting structure of the rotor and the structure clamping the slotless armature winding. Concentration of effort on selected problems is taking place at the expense of a general design method, resulting in the loss of relationships between the results of analyses of individual phenomena. The design of power engineering units (output exceeding 1 GVA) necessitates the development of computational methods which are suitable for an analysis of phenomena that are negligible or unknown in conventional machines. On the one hand, these methods must describe with the greatest possible accuracy physical phenomena, and on the other, they must be interrelated to the maximum possible degree. This follows, among other things, from economic prerequisites--the cost of building a unit with output on the order of magnitude 1 GVA is too high to permit the application of traditional methods for improving the design. Therefore, a need exists for formulating an algorithm which will determine rationally basic design magnitudes of superconducting generators on the basis of a synthesis of the results of analyses of individual phenomena.

Description of Algorithm

The first activity during the design of a synchronous superconducting generator is selection of the structure. Other considerations pertain to a machine with the design envisioned for this type of converter in the output range 0.3 to 3 GVA [6]. Fig. 1 shows the basic elements of the electromagnetic system and their mutual arrangement. The main purpose of using the algorithm is the

determination of basic geometric dimensions which will correspond, as accurately as possible, to the optimal solution. These dimensions are determined by determining coefficients defined by their ratios. The following dimensional coefficients are used (Fig. 1)

$$c = \frac{R_{fi}}{R_{fo}}; \quad d = \frac{R_{ei}}{R_{wo}}; \quad x = \frac{R_{fo}}{R_{wo}}; \quad y = \frac{R_{so}}{R_{ci}};$$

$$z = \frac{R_{fo}}{R_{ci}}; \quad v = \frac{R_{so}}{R_{ci}}; \quad u = \frac{R_{ci}}{R_{co}}; \quad L = \frac{l_{w}}{R_{co}}. \tag{1}$$

[0 = calculated; c = armature; w = filling; v = calculated; e = shield; cz = frontal]

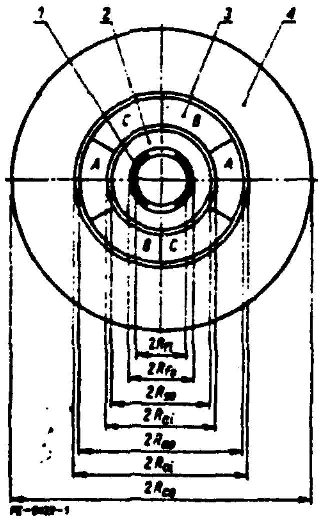

Fig. 1. Electromagnetic system of superconducting generator

1. superconducting excitation winding
2. rotor shielding system
3. slotless stator winding
4. magnetic shield of stator

The next steps in formulating the design algorithm are: determination of the structural equation of the machine and setting up criteria for selection of dimensions. Introduction of these criteria in the structural equation reduces the number of successive approximations in the endeavor to design a suitable optimal structure.

In the preliminary design stage, these criteria are determined by assuming great simplifications in detailed computational methods, which allows one to narrow down the range of possible variations of some dimensions. The next step in the algorithm is proper sequencing of detailed electromagnetic, mechanical, and heat computational methods and their assignment to a common base constituting a description of the electromagnetic fields in the machine. Quality measures of the design are verified on the basis of the results of detailed calculations and if necessary the dimensional coefficients adopted in the initial stage are corrected. The algorithm for this procedure is presented in Fig. 2 in the form of a block diagram.

Structural Equation of Machine

The fundamental structural equation of a superconducting machine is the same as that for a conventional machine [4]

$$P = \frac{\pi^2}{\sqrt{2}} k_{1w} B_{\delta} A_s D^2 l n_s \tag{2}$$

The equation in this form is not suitable for the design of superconducting generators for two reasons: first, it does not take into account all basic dimensions of the machine (Fig. 1); second, the discrepancies resulting from the simplifying assumptions made during its derivation are so great for the machines under consideration that the equation should only be treated as a preliminary descriptive equation. The complete structural equation was obtained by relating the power of the superconducting machine to its basic dimensions, current densities of windings, and angular velocity [2]:

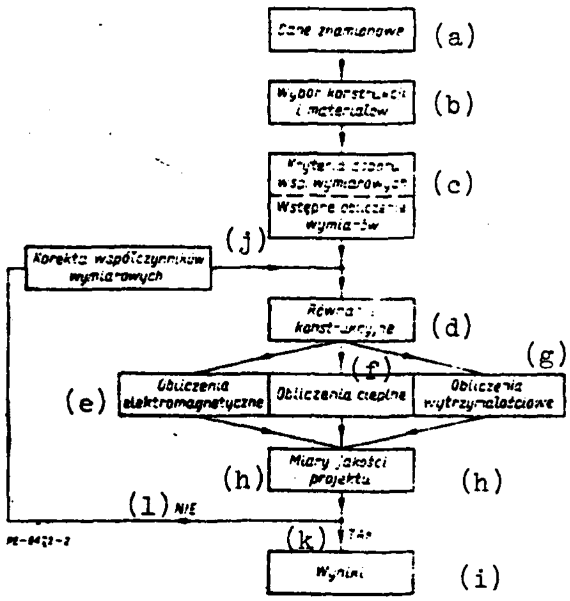

Fig. 2. Block diagram of algorithm determining basic dimensions of synchronous superconducting machine

Key: a. Ratings
b. Selection of structure and materials
c. Criteria for selection of dimensional coefficients/Initial calculation of dimensions
d. Structural equation
e. Electromagnetic calculations
f. Heat calculations
g. Strength calculations
h. Measures of quality of design
i. Results
j. Correction of dimensional coefficients
k. Yes
l. No

$$S_N = \frac{\pi^2}{12}\omega\mu_0(1-d^2)\lambda_a k_{wa}^2 j_{aN}^2 R_{ao}^4 l_{ae}\left[\sqrt{\left(\frac{12}{\pi^2}\frac{k_{wf} j_{fN}}{k_{wa} j_{aN}}\frac{\lambda_{ad} l_{ez}}{\lambda_f l_{ae}}\frac{1-e^2}{1-d^2}x^3\right)^2 - \cos^2\varphi_N} - \sin\varphi_N\right] \quad (3)$$

This equation can be simplified by assuming some quantities to be constant, for example, the filling factors of properly made windings [2] are: $k_{wa} = 0.25$;

$k_{wf} = 0.625$, while the ratio of the calculated length of the machine l_{0x} to the calculated length of the armature winding l_{0a} is approximately equal to 0.7. In addition, assuming $p = 1$, Eq. (3) takes on the form

$$S_N = 20{,}293 \cdot 10^{-6} (1 - d^2)^2 \lambda_d j_{aN}^2 R_{ao}^4 l_{oa} \times$$
$$\times \left[\sqrt{\left(1{,}69 \frac{\lambda_{ad}}{\lambda_d} \frac{1 - c^2}{1 - d^2} x^3 \frac{j_{fN}}{j_{aN}}\right)^2 - \cos^2 \varphi_N} - \sin \varphi_N \right] \tag{4}$$

Eq. (4) contains, besides the ratings S_N, $\cos\phi_N$, the ratios of the radii of the windings: c, d, x, the current densities of the windings j_{fN}, j_{aN}, and the product $R_{ao}^4 l_{oa}$. The unit permeances λ_{ad} and λ_d are functions of the coefficients c, d, y [1]. The fundamental structural equation of the machine is obtained by transforming relation (4) in such a way that the outer diameter of the armature winding is expressed in terms of the dimensional coefficients (1)

$$R_{ao}^3 = \frac{10^6 S_N}{20{,}293 (1 - d^2) \lambda_d l_a j_{aN}^2 \left[\sqrt{\left(1{,}69 \frac{\lambda_{ad}}{\lambda_d} \frac{1 - c^2}{1 - d^2} x^3 \frac{j_{fN}}{j_{aN}}\right)^2 - \cos^2 \varphi_N} - \sin \varphi_N \right]} \tag{5}$$

Criteria for Selection of Dimensions

The variability ranges of the current densities j_{fN} and j_{aN} in Eq. (5) are constant. The armature current density is determined by the adopted cooling system and is in the range $(2.5 \text{ to } 10) \cdot 10^6$ A/m^2. The excitation winding current density is determined by the critical magnitude of the current in the superconductor that is used, which for the given material depends on the temperature and the external magnetic field strength. The characteristics $j_{cr} = f(T,H)$ determined for short specimens can only be used for preliminary calculations. After the design of the excitation winding structure and selection of the catalogued conductor, the excitation current density assumed earlier can be corrected using the catalogued characteristic $I_{cr} = f(T,H)$. The critical current density for conductors produced at the present time are in the range $(200 \text{ to } 400) \cdot 10^6$ A/m^2 at T = 4.2°K and H = 397.5 A/m. Assuming that the rated

excitation current density is equal to two-thirds of the critical density, we obtain a practical range for the magnitude of the excitation current density $(130 \text{ to } 270)\cdot 10^6\ A/m^2$.

The dimensional coefficients c, d, x, y, L follow from the criteria assumed in the design. In the case of a superconducting turbogenerator, these criteria may be:

1. dynamic stability
2. critical velocities of rotor
3. mechanical stresses in stator and shielding system in a short-circuit surge state
4. maximum deformations of rotor in transient states
5. time constant of shielding system
6. free vibration of stator core.

Criteria for selection of dimensions follow from a detailed analysis of the given quantity (dynamic stability), mechanical stresses in rotor, etc., which are reduced to the admissible ranges of the values of the dimensional coefficients using the properties of the materials intended for use and the mechanical, electromagnetic and thermal properties of the designed structure. Because many analyzed criterion quantities are mutually opposed, an attempt should be made to determine a sufficiently large number of them already in the first design stage. This allows one to limit substantially the number of design stages.

Detailed Calculations and Quality Measures

Detailed calculations include electromagnetic, heat, and strength calculations carried out for steady operation, asymmetry of load, and short-circuit surge. The purpose of electromagnetic calculations is above all a determination of the distribution of the field in the machine. This constitutes a basis for calculating losses in individual structural elements, electrodynamic volume forces, electromagnetic parameters, etc. These calculations must take into account, as needed, the finite axial dimensions of machine elements and the effect of coil outhangs.

Heat calculations lead to a determination of the distribution of temperature fields, heat fluxes, and consumption of coolant in cooling systems. They also allow one to calculate expansion (dilatation) forces of elements operating at great temperature gradients.

Strength calculations allow one to determine mechanical stresses and strains in structural elements in abnormal states, in particular, in a short-circuit surge state, while rotor strength calculations allow one to improve the accuracy of the dimensional criteria already in the initial design stage. Detailed calculations should in fact lead to relationships between parameters of the investigated phenomena and the dimensional coefficients of the machine. However, because of the complexity of these phenomena, in many cases satisfactory analytical solutions have not yet been obtained. In particular, this applies to the distribution of fields in frontal zones, stator and shielding system vibrations, etc. Until these phenomena are fully described, simplified computational methods must be used.

The quality measures of the design include two groups of indicators. Coefficients of strength, heat given up, etc. constitute the first group. Verification of the values of these coefficients and their comparison with the admissible values decides whether correction of the dimensional coefficients is necessary. Operational indicators of the generator (mass, efficiency, idle run characteristic, reactance, etc.) constitute the second group of measures. The values of these parameters constitute a basis for an evaluation of the design assumptions and possible corrections of dimensional coefficients within the ranges determined by appropriate criteria.

Examples of Calculations

To illustrate proper selection of individual dimensions on the basis of the described criteria, we selected from a large set of problems the problem of the critical velocity of the rotor and the problem of the time constant of the shielding system.

In regard to the rotational velocity of the rotor of a superconducting generator, it is required that it be smaller than the first critical velocity or that it lie between the first and second critical velocity. Using the first condition, one can assume [2]

$$n_N \leqslant \frac{2}{3} n_{k1} \tag{6}$$

Simplifying the problem to the case of a two-stage rotor made from nonmagnetic steel (Fig. 3), we obtain a relation for the first critical velocity as a function of the dimensions of the rotor [2]:

$$n_{k1} = 3{,}04 \cdot 10^5 \frac{R_{so}}{l_c^2} \tag{7}$$

Substituting condition (6) in (7), we obtain the relation

$$\frac{l_c}{R_{so}} = \frac{8{,}2}{\sqrt{R_{so}}} \tag{8}$$

which is graphically illustrated by the plot in Fig. 3. The calculated length of the armature winding $l_{0a} = 1.4 \cdot l_{a\ mean}$ is approximately equal to the length of the armature sleeve, whereas the outer radius of the armature winding R_{ai} is greater than the outer radius of the rotor (by an amount equal to the size of the gap and the thickness of the insulation of the base of the armature winding). Assuming $R_{ai} = 1.2R_{so}$, we obtain an upper bound for the dimensional coefficient L, which occurs in structural equation (5). Hence, during selection of the value of L, advantage can be taken of the graph in Fig. 3 and of the inequality

$$L \leqslant 0{,}833\, d \frac{l_c}{R_{so}} \tag{9}$$

In regard to the time constant of the shielding system, it is required that it be 1 to 2 times greater than the reciprocal of the angular frequency of the damped field [3]. In the case of fluctuations, this is equivalent to the requirement

$$T_e \geqslant 0{,}2\ \mathrm{s} \tag{10}$$

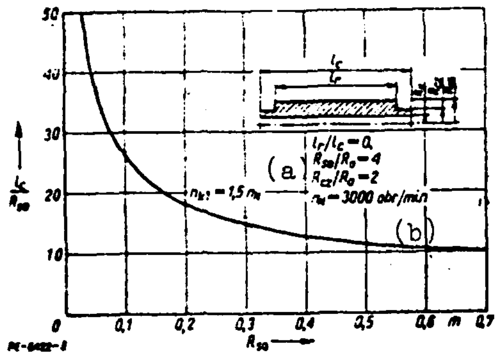

Fig. 3. Effect of rotor dimensions on its first critical velocity

$1_r/u_c = 0.8$; $R_{so}/R = 4$; $R_{front}/R_0 = 2$;
$n_N = 3000$ rpm

Key; a. $R_{front}/R_0 = 2$
b. rpm

Therefore the damping system must consist of two shields: a damping shield operating in the surrounding air temperature and suppressing fields with high frequencies, and a cryogenic shield operating at helium temperature and ensuring an adequately large time constant of the shielding system. The system of shields must be protected mechanically by suitable nonmagnetic steel layers, which together form a multilayer electromagnetic system. Determination of the thickness and subsequently also of the radii of individual layers is of fundamental importance for the rotor structure.

The time constant of a cylindrical electromagnetic shield, without taking into account the yoke of the stator, is calculated from the relation

$$T_{eo} = \frac{1}{2} \gamma \mu_0 R \Delta \tag{11}$$

or from the relation taking into account the yoke of the stator

$$T_e = T_{e\infty}\left[1+\left(\frac{R}{R_{ct}}\right)^2 l\right] \tag{12}$$

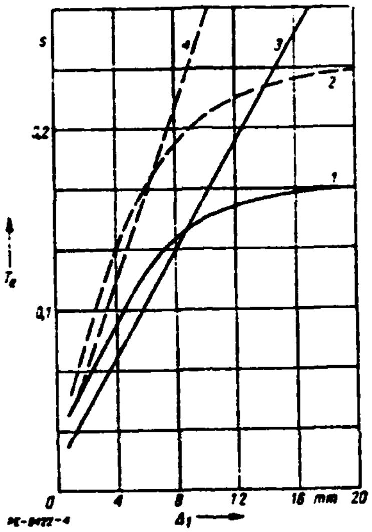

Fig. 4. Time constant of shielding system versus thickness of damping shield for f = 2 Hz, p = 1, ν = 1, R_{so} = 0.474 m

1. taking into account stator yoke
2. not taking into account stator yoke
3. according to relation (11)
4. according to relation (12)

Relations (11) and (12) were obtained assuming a uniform distribution of the density of eddy currents in the shield and for $f \to 0$ [5]. In reality, the current distribution deviates considerably from a uniform distribution and, in addition, depends on the frequency of the field, resistivity, and dimensions of the shield. Therefore, in detailed calculations, the time constant is determined on the basis of the actual distribution of the field in the multilayer shielding system. We considered a four-layer system consisting of an external

damping shield, a supporting structure, a vacuum, and a cryogenic shield. The time constant of the system is determined from the relation [3]

$$T_e = \frac{1}{\omega}\arctan\left[\mathrm{Arg}\,j\,\frac{\Gamma_1(R_{so})}{Y_1(R_{so})}\right] \quad (13)$$

in which $\Gamma_1(R_{so})$, $Y_1(R_{so})$ are the values of the eigenfunctions $\Gamma_1(r)$ and $Y_1(r)$ describing the distribution of the field in a cylindrical multilayer shield [7]. Fig. 4 shows the time constant of the shielding system as a function of the thickness of the external damping shield.

The minimum thickness of the damping shield at which the entire system has an adequate time constant is obtained from the plot of the curves presented in Fig. 3. This value, combined with strength calculations, constitutes one criterion for selecting the outer diameter of the rotor.

Conclusions

The idea of an algorithm for the design of basic dimensions of electromechanical converters applies to all types of machines in which problems occur that have not been encountered so far in design practice and for which a structural equation can be set up relating the ratings to these dimensions. The design of a rational structure, that is, a structure substantiated by the present level of knowledge, is the reason for using such an algorithm.

The degree of perfection of the superconducting synchronous generator design depends on the number and importance of criteria used for selecting dimensions. An increase in the number of criteria, contributing to greater computational accuracy, is limited by present-day possibilities of an analytical description of phenomena. The selection of criteria according to their importance entails elimination of criteria providing constraints on dimensional coefficients which lie within the ranges determined by other criteria.

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